Impacts of Ocean Waves on the Atmospheric Surface Layer: Simulations and Observations

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LONG-TERM GOALS

The long term objective of our research is to advance the understanding of air-sea interaction and the coupling between the atmospheric and oceanic boundary layers (the ABL and OBL) mediated by the surface gravity wave field, in order ultimately to develop better parameterizations of the boundary layers and surface fluxes for coupled, large-scale numerical models. Turbulence-resolving, large-eddy and direct numerical simulations (LES and DNS) are the main tools to be used to investigate interactions among the ABL, OBL, and the air-sea interface. Using numerically generated databases, we intend to investigate: (1) vertical heat and momentum fluxes carried by wave-correlated winds and currents; (2) enhanced small-scale, turbulent energy, mixing, and dissipation due both to enhanced wave-correlated wind and current shears and to wave breaking; and (3) wave-averaged influences due to mean Lagrangian currents (Stokes drift) that give rise to coherent Langmuir circulations in the ocean. These mechanisms will be considered for a variety of surface wave states. Finally, we intend to make an effort to connect our simulation results with the proposed Coupled Boundary Layers Air-Sea Transfer (CBLAST) field campaigns (Edson *et al.* 2007; Black *et al.* 2007; Chen *et al.* 2007).

OBJECTIVES

Our recent research objectives have focused on understanding the interaction between imposed surface gravity waves and stratified turbulence in the atmospheric boundary layer. Specifically we are using LES to help interpret the observations collected from the Air-Sea Interaction Tower (ASIT) during the low-wind CBLAST field campaign.

APPROACH

We are investigating interactions among the ABL, OBL, and the connecting air-sea interface using both LES and DNS. The premise behind this approach is that the fundamental processes that lead to air-sea coupling will manifest themselves in three-dimensional, time-dependent simulations. The capabilities of the LES code used here are documented in Moeng (1984), Sullivan *et al.* (1994), Sullivan *et al.* (1996), McWilliams *et al.* (1997), and Sullivan *et al.* (2007a). A

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14. ABSTRACT

The long term objective of our research is to advance the understanding of air-sea interaction and the coupling between the atmospheric and oceanic boundary layers (the ABL and OBL) mediated by the surface gravity wave field, in order ultimately to develop better parameterizations of the boundary layers and surface fluxes for coupled, large-scale numerical models. Turbulence-resolving, large-eddy and direct numerical simulations (LES and DNS) are the main tools to be used to investigate interactions among the ABL, OBL, and the air-sea interface. Using numerically generated databases, we intend to investigate: (1) vertical heat and momentum fluxes carried by wave-correlated winds and currents; (2) enhanced small-scale, turbulent energy, mixing, and dissipation due both to enhanced wave-correlated wind and current shears and to wave breaking; and (3) wave-averaged influences due to mean Lagrangian currents (Stokes drift) that give rise to coherent Langmuir circulations in the ocean.

15. SUBJECT TERMS

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companion DNS code that accommodates a temporal and spatial varying lower boundary utilizing a co-located grid architecture is described in Sullivan *et al.*(2000). We are collaborating with James Edson (U. Conn.) and Tihomir Hristov (Johns Hopkins U.) using observational periods from CBLAST that feature light winds and strong swell to validate and compare with our LES solutions, and with Ken Melville (Scripps Institute of Oceanography) on wave modeling for the OBL.

WORK COMPLETED

During the past fiscal year we completed two journal articles (Sullivan *et al.* 2007a,b) and a meeting paper (Sullivan *et al.* 2007c) on our CBLAST ABL and OBL work. The journal articles were revised and are now accepted for publication (see Publication Section). Sullivan *et al.*(2007a) presents an analysis of the CBLAST winds and waves collected from the Air-Sea Interaction Tower, describes the computational algorithm used in our wave following LES code, and compares the CBLAST observations with LES results. Highlights from this paper are briefly described here (see Results Section). Sullivan *et al.*(2007b,c) describes our OBL LES code with stochastic breaking waves and wave-current interactions. It focuses on simulation results at wind speeds of 15 ms^{-1}, but higher winds $\mathcal{O}(30)$ ms^{-1} are also considered. The analysis compares flow structures and statistics for OBLs driven by uniform stress and random breaking waves. Simulation results also demonstrate how breaking waves can interact and stimulate Craik-Leibovich (CL2) instabilities.

In related work, we expanded our database of LES solutions for flow over waves to include a broader range of wind-wave conditions. Simulations with wave age $C_p/U_a = (1, 2)$ were generated for waves following, opposing, and crossing the surface layer winds. These results were presented at an ONR Ship Hydrodynamics Meeting on "Ship Motions & Loads". Also, we continue to analyze observational data obtained from the field campaign OHATS (Ocean Horizontal Array Turbulence Study) with the objective of identifying light-wind conditions with wave effects to validate the predictions of the LES. The OHATS and CBLAST low-wind databases are complimentary: the field site for OHATS was identical to the CBLAST low-wind campaign and also used the ASIT. During CBLAST and OHATS the surface winds are generally ~ 5ms^{-1} and the wave fields are frequently dominated by 100m swell generated by distant fronts. Thus the winds and waves are often in a non-equilibrium state. Further information about the objectives of and results from OHATS can be found in the report by Sullivan *et al.*(2005a) and at web sites http://www.atd.ucar.edu/rtf/projects/OHATS04/ and http://www.whoi.edu/science/AOPE/dept/OHATS/intro.html.

RESULTS

Measurements from the CBLAST Low-wind field campaign Edson *et al.*(2007) show that the winds and waves in the marine surface layer are frequently in a state of disequilibrium in light to moderate wind conditions $U_a \leq 10$ m s^{-1} . Long-wavelength, fast-moving waves generated by distant storms often dominate the local wave height variance and spectrum and propagate in arbitrary directions relative to the local wind. In terms of a bulk wave age $C_p/U_a \cos\phi$, where C_p is the phase speed of the peak in the wave height spectrum and ϕ the wind-wave angle, the wave age is most often either negative or greater than the equilibrium value of 1.2 (see figure 1). In low wind conditions swell is then an important source of variability in measurements of the surface drag coefficient C_D.

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To examine the interaction between atmospheric turbulence and swell, a large eddy simulation (LES) model of the planetary boundary layer (PBL) is developed with the capability of imposing propagating sinusoidal modes at its lower boundary. The code is used to simulate a variety of PBLs with an emphasis on situations with wind following waves, wind opposing waves, and stationary bumps. The LES results illustrate the importance of wave phase speed relative to wind speed and the orientation of winds and waves. Surface-layer winds are modulated by the structure of the near-surface pressure field (*i.e.,* the resolved surface form stress) as shown in figure 2. In flow over stationary bumps or wind opposing waves, the resolved form stress is negative, while for wind following waves, the resolved form stress is positive. In the latter situation LES predicts momentum transfer from the ocean to the atmosphere and the generation of a low-level jet; the magnitude of the winds at $z \sim [10, 20]$ m are about 10% greater than the geostrophic wind and vary with surface heating. Our interpretation suggests that the jet formation results from a wave-induced turbulent momentum flux divergence that accelerates the flow and a retarding pressure gradient both of which are opposite to the momentum balance in classical shear boundary layers. In a neutrally stratified PBL, the presence of a low-level jet reduces the mean shear between the surface layer and the PBL top, leading to a near collapse of turbulence in the PBL. The mean wind profile, turbulence variances, and vertical momentum flux are then dependent on the nature of the wave field, the wind-wave orientation, and wave age. The LES predictions for the dependence of vertical momentum flux on wave age are also found in the CBLAST observations (see figure 3). The LES results with moving waves show important differences compared with rough-wall boundary layers and flow over stationary bumps (*i.e.,* hills).

The current LES with its monochromatic wave represents an idealization of a light wind PBL with swell. In the open ocean, a multi-component wave field can simultaneously be a sink and source of momentum for the atmosphere, with short (long) waves extracting (imparting) momentum. The sign and magnitude of the near surface fluxes will then depend on several factors including the orientation of winds and waves and the relative location of the wave spectral peak and the mean wind. Flux parameterizations (Fairall *et al.* 2003; Edson *et al.* 2006) thus require information about the wave field in addition to the winds.

IMPACT/APPLICATIONS

In typical ocean conditions CBLAST data shows that local winds and waves are frequently in disequilibrium due to the presence of swell generated by distant storms. Swell leading, opposing, or running at angles to the surface winds modifies the vertical momentum flux between the atmosphere and ocean. Hence, Monin-Obukhov surface similarity theory needs to account for sea state.

TRANSITIONS & RELATED PROJECTS

We are currently engaged in analyzing data collected during the Ocean Horizontal Array Turbulence Study (OHATS). This is a joint effort between NCAR, Woods Hole Oceanographic Institute, and Pennsylvania State University. The goal of OHATS is to gather data about the impact of surface waves on subgrid-scale variables that are modeled in LES codes. Also, we are participating in the new DRI "High Resolution Air-Sea Interaction" focused on high winds and large waves. In related work with ONR Ship Hydrodynamics we created and analyzed an LES database of surface layer winds for non-equilibrium conditions, *i.e.,* with variations in wave age and wind-wave alignment.

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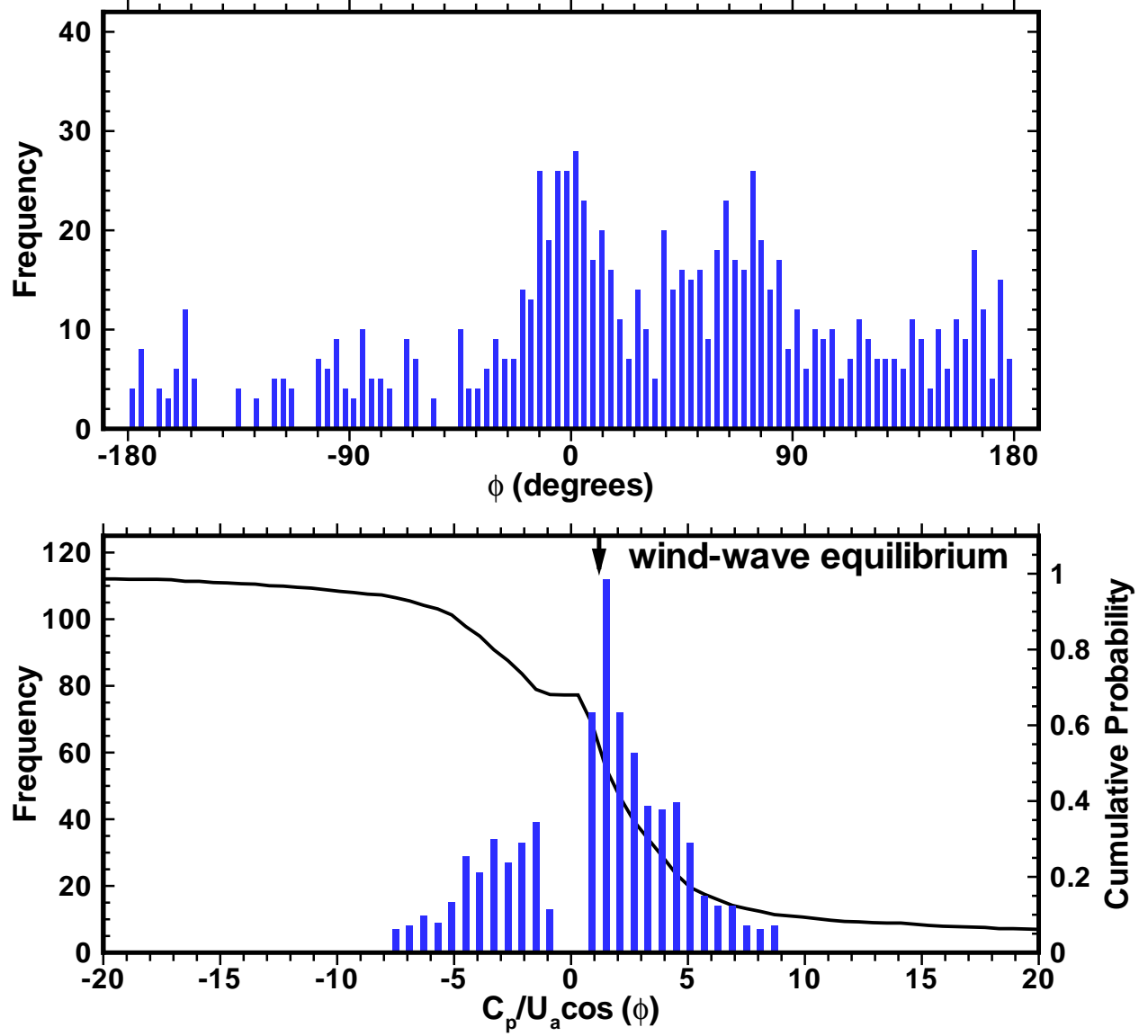
Figure 1: *Frequency histogram of wind-wave angle ϕ (upper panel) and wave age $C_p/U_a \cos \phi$ (lower panel) during CBLAST for all wind-wave conditions. In the lower panel the solid line is the cumulative probability sum $1 - \int_0^x p(x')dx'$ where $p(x)$ is the probability density function. These histograms demonstrate that most often the winds and waves are in disequilibrium at the CBLAST low-wind site.*
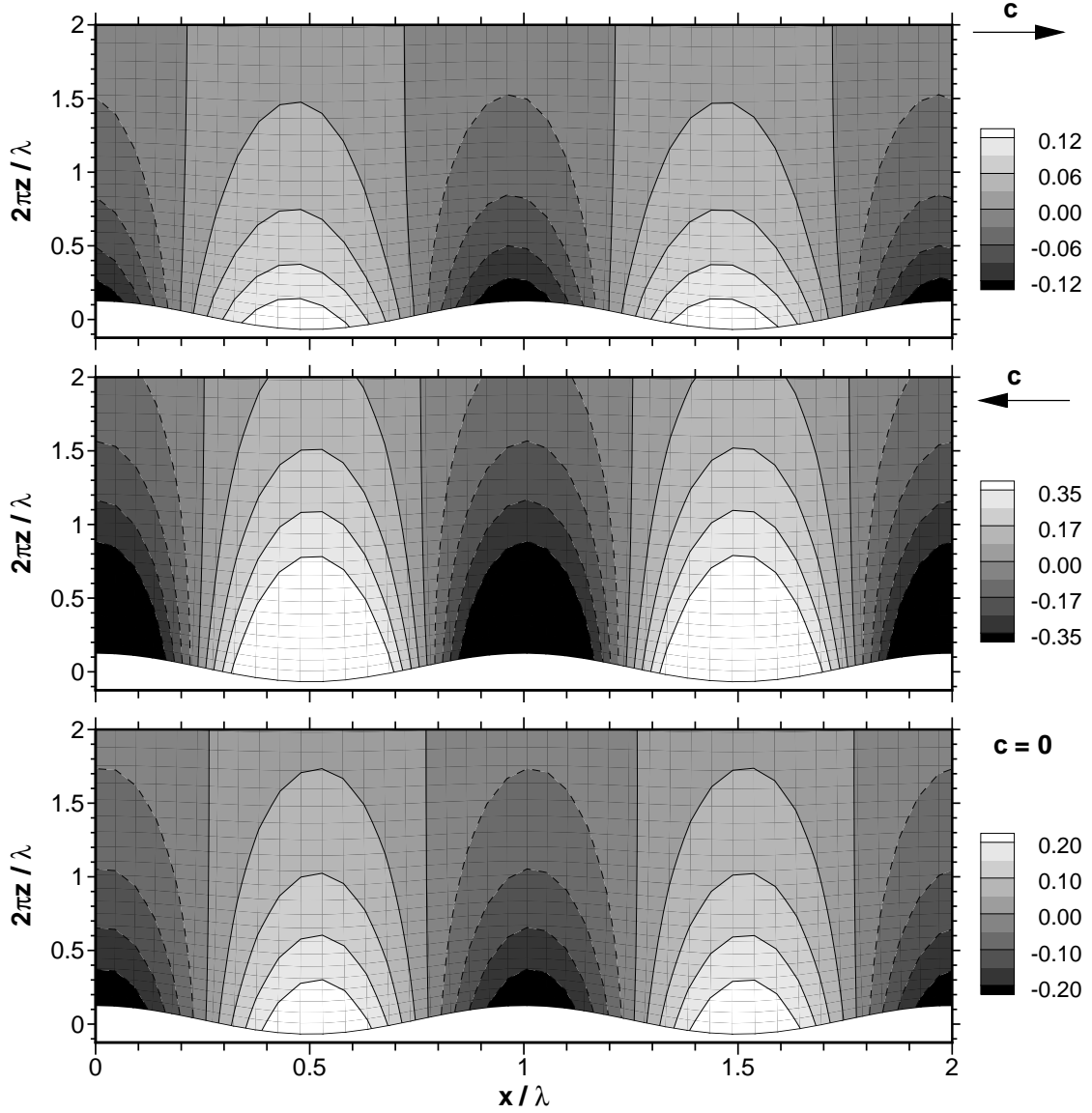
Figure 2: *Contours of the non-dimensional and $y-$averaged pressure field $[p^*]/U_g^2$ close to the water surface for cases with moving and stationary waves in LES. The winds are from left to right. Negative contours are indicated by dashed lines. Top panel wind following waves; middle panel wind opposing waves; and, bottom panel stationary bumps. The vertical and horizontal coordinates are made dimensionless with the surface wavelength λ. The large-scale geostrophic wind is U_g. Notice the slight asymmetry in the pressure contours relative to the underlying waveform which induces a different response in the atmospheric surface layer winds.*
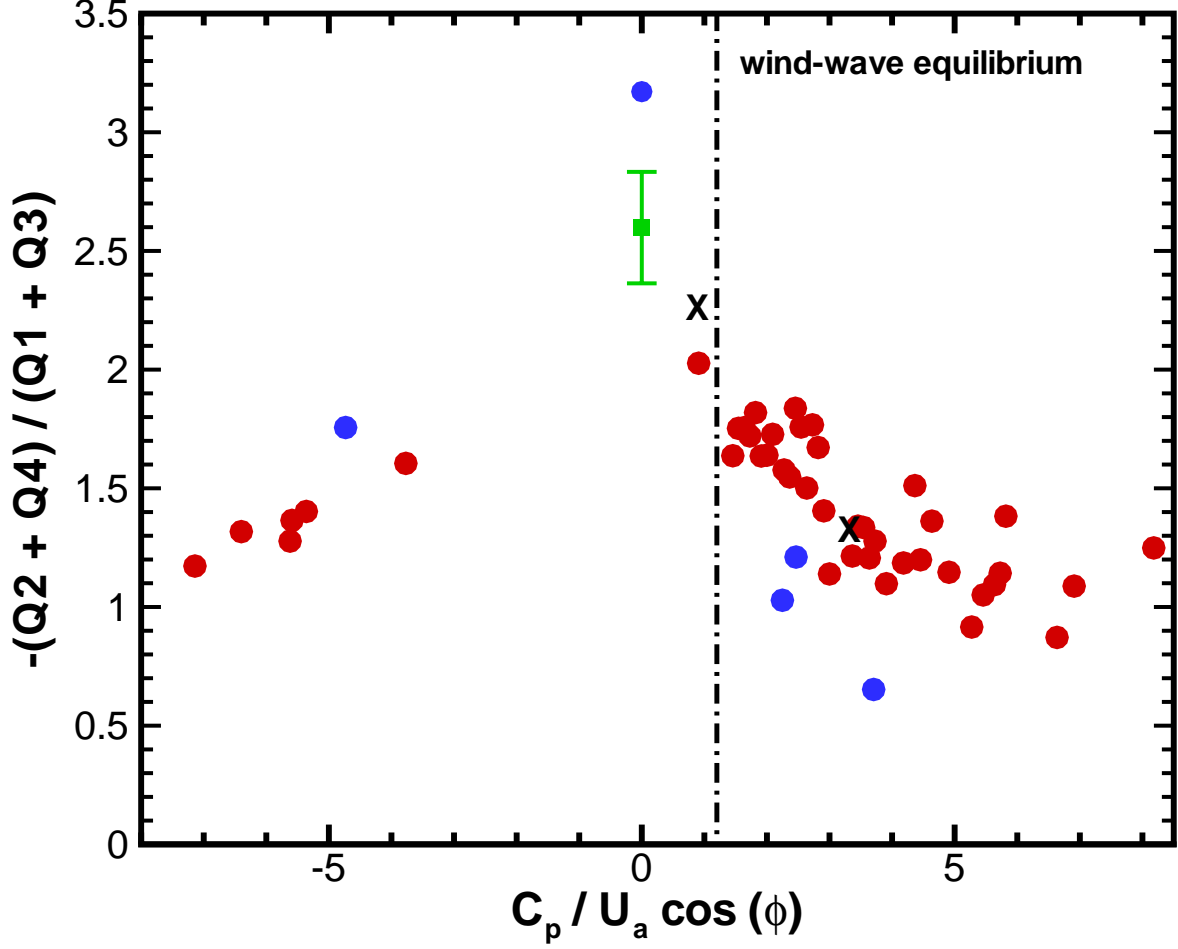
Figure 3: *Quadrant analysis of the vertical momentum flux in the marine surface layer for varying wave age. Results are for conditions with aligned winds and waves, viz., waves leading or opposing the winds. The dashed vertical line indicates wind-wave equilibrium. The momentum flux from the measurements and LES is conditionally sampled (split) into four quadrants $[Q1, Q2, Q3, Q4]$ according to the rules: $[Q1 > 0$ where $u' > 0, w' > 0]$, $[Q2 < 0$ where $u' < 0, w' > 0]$, $[Q3 > 0$ where $u' < 0, w' < 0]$, $[Q4 > 0$ where $u' > 0, w' < 0]$. Solid red circles are CBLAST measurements. The observations of Smedman et al.(1999) are denoted by $\mathbf{X}$ and results for flow over stationary roughness (note wave age = 0) Sullivan et al.(2003) are indicated by the green square with error bars. The LES results for winds following and opposing waves are the solid blue circles.*